BREAKTHROUGHS IN LOW-PROFILE LEAKY-WAVE HPM ANTENNAS

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14. ABSTRACT
This report describes progress during the 7th quarter of this program and summarizes the current status of the research. Technical activities this period emphasized pursuit (still in progress) of recipes/scripts to guide engineers in design of "Rotated Aperture Waveguide Sidewall-Emitting Antennas" (RAWSEAs). This configuration is important to address, because it features the lowest-profile of all the antennas under investigation here. However, SARA's handful of aperture-efficient RAWSEA designs to date have required time-consuming iterative numerical modeling to obtain configurations with predicted performance approaching a FAWSEA of similar aperture area. We are confident this can be improved and are working on "standard" designs and scripts for the RAWSEA, such as those we documented earlier for the (Flat) FAWSEA and (Curved) CAWSEA. Some of the challenges and possible solutions are discussed here.

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1. INTRODUCTION

This is SARA's 7th Quarterly Report for "Breakthroughs in Low-profile Leaky-Wave HPM Antennas," a 37-month Basic Research effort sponsored by the US Office of Naval Research (ONR). This work includes fundamental theoretical analyses, numerical modeling, and related basic research. Objectives include to discover, identify, investigate, characterize, quantify, and document the performance, behavior, and design of innovative High Power Microwave (HPM, GW-class) antennas of the *forward-traveling*, *fast-wave*, *leaky-wave* class.

1.1. Overview of Previous Activities (1st thru 6th Quarter)

During the *first* quarter, we prepared and established useful equations and algorithms for predicting reflections and transmission of incident TE waves from parallel-wire grills, dielectric windows, and combinations of wire grills with dielectric windows, in problems reducible to purely H-plane (2D) representations. We then applied this theory to guide the design of high-gain configurations (again, limited to 2D, H-plane representations) for linear, forward traveling-wave, leaky-wave antennas. The theory built upon equivalent circuit methods and wave matrix theory, which provided useful formalisms upon which we continue to build.

During the *second* quarter, we pursued initial extensions of the previous work into three dimensions, in order to include phenomena with E-plane dependencies. We succeeded in adding into the wave-matrix formalism the reflection/transmission properties associated with the transition to free space from a *finite-width* leaky-wave channel, including the edge-tapering essential to HPM applications. These geometric aspects do not arise in analyses confined to the H-plane alone. Our 3D analyses were somewhat more reliant on numerical models than in the 2D analyses, due to the greater complexity of identifying and/or building practical analytic approaches capable of addressing true 3D geometries of interest.

During the *third* quarter, we explored channel-to-channel coupling (aka, mutual coupling) which (as we have noted earlier) is an important design concern, since it can impact antenna performance significantly in terms of gain, peak power-handling, and impedance matching. Our approach leveraged mostly numerical methods, along with some intuitive arguments, as we explored designs exhibiting different degrees of mutual coupling between adjacent channels. As past and current antenna literature attest, mutual coupling analyses are non-trivial; suffice to say, there is still much work to be done in this area.

During the *fourth* quarter, we continued to study and employ wave-matrix based methods, but with less success than before in applying this approach to *improve* or *optimize* the initial designs. The formalism itself is still valid, but offers reduced practical rewards once an *initial* (i.e., not fully-optimized) geometry (e.g., grill, window, channel depth, etc.) is derived from the more basic-level principles. At that stage, we are finding that further optimization is currently best proceeding via numerical means. Additional work in the fourth quarter led us to identify *new aperture geometries* of potentially-significant practical value, which included the "BAWSEA" and "GAWSEA". These configurations may significantly extend the utility of leaky-wave antenna technology to support integration on more challenging platforms.

During the *fifth* quarter, we designed, analyzed, and documented representative high-performance FAWSEA and CAWSEA antennas suitable for designation as "standard" or "recommended." The configurations we described were scalable with wavelength. These are the initial entries in a library of antennas that will continue to be built throughout this program.

During the *sixth* quarter, we performed additional investigation of designs to support the newer curved apertures, especially the "Bent Aperture Waveguide Sidewall-emitting Antenna" (BAWSEA). We presented this work at the 17th Annual Directed Energy Professional Society (DEPS) Symposium in Anaheim, CA, on March 4th, 2015. Our full slide presentation, entitled "Advances in Low-Profile Leaky-Wave Conformable Antennas for HPM Applications," was included in the unclassified proceedings CD that was recently distributed by DEPS to all the conference attendees.

For more information, we encourage the reader to refer our earlier *Quarterly Reports #1* thru *#6.*

1.2. Overview of Recent Activities (7th Quarter)

During this quarter, we continued to pursue activities in both the "Fundamental Analyses & Models" tasks {2.x} and the "Optimal/Recommended Designs" tasks {3.x}. These tasks do not always lead us in the same directions. The *simplest* possible designs are generally most-amenable to traditional theoretical treatments, but are typically *non-optimal* in terms of overall performance. A good example is the cross-sectional geometry[1] of the aperture window, where including a tapered center transition (see Figure 1) was found (in numerical-models) to yield improved performance. We incorporated this feature into our standard/recommended scalable designs[2] of the FAWSEA and CAWSEA, despite the fact that the theoretical formalism (which guided the design-recipe development) actually assumes that the window is featureless (flat) on both its inner and outer surfaces.

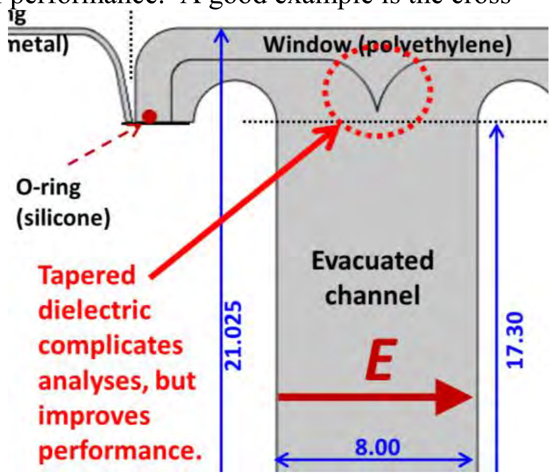

Figure 1. Part of a cross-section of a high-performance FAWSEA design. Some of the features included are challenging to treat theoretically.

Aside from the rotated channels (e.g., see Figure 2), the RAWSEA configuration introduces a non-negligible separation between the leaky wire-grill and the region of the E-plane channel flare and window. From our earlier wave-matrix analyses, this separation should, *a priori*, be directly representable as a finite-length TL stage, with an *effective* length (to be extracted and tabulated via numerical models if necessary) to be included in the root-finding process (MatLab scripts[3]) for determining the wire sizes (for a fixed wire-spacing). Unfortunately, in many cases, we found that our most *intuitive* approach to including this term led to wires *unworkably thin* or even *non-existent* (i.e., no solution found to the resulting set of equations). A potential alternative is to increase the wire spacing (to increase local leak rates) so that thicker and thus more practical wires can be used instead.

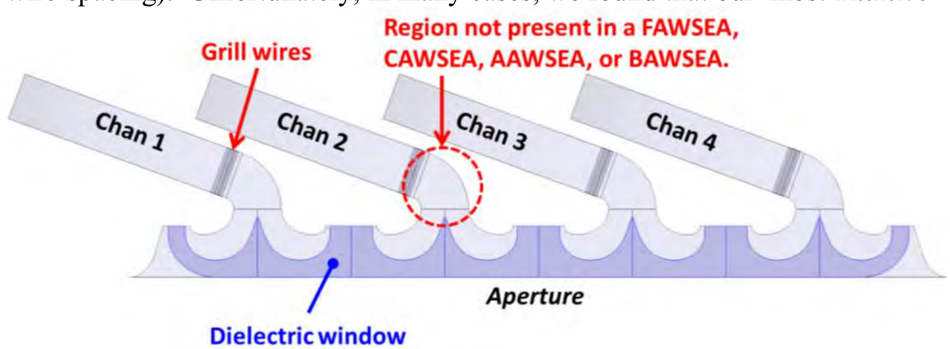

Figure 2. A RAWSEA cross-section[4] necessarily includes a space *between* the leaky-grill and aperture region. This can complicate analyses, design, and impedance-matching across desired bands.

However, this risks violating the constraint that the wire grill should provide a spacing tight enough to be approximated by the theory of a continuously-leaky interface. That assumption has been important in the theoretical approach so far. Another option, which we are only beginning to explore, is to generalize our

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[1] Cross-section borrowed from our "recommended" FAWSEA design. See our earlier reports.
[2] Our 5th Quarterly Report and recent (March 4, 2015) presentation at DEPS detailed our recommended FAWSEA and CAWSEA designs.
[3] See our earlier reports for examples.
[4] Example borrowed from a design prepared by the PI in late 2012.

recipes/scripts to explicitly generate unequally-spaced wire grills. Regardless, there may exist a subset of RAWSEA-style geometries that are “pathological,” i.e., which correspond to channel-to-aperture spacings that should simply be avoided. This appears analogous to the classic problem of preparing cable runs from radio transmitters with antenna tuners to their physically-separated antennas – certain transmission-line lengths must be avoided[5] so that impedance-matching conditions can be realized. We are currently revisiting the details of applying the aforementioned wave-matrix methodology to RAWSEA. Section 3 discusses some recent technical work on RAWSEA models to confirm the applicability of the formalism to the curved section. This is improving our confidence that if applied with sufficient care, the formalism must yield reasonably-good RAWSEA designs. We will also note some related activities we are pursuing in the overall program.

Finally, we are pleased to report here that SARA has purchased[6] and our PI will soon be employing a more powerful computer to better support the intensive RF computations needed by this research and by our other advanced HPRF/HPM antenna design R&D programs. The new machine is a Dell T7910 workstation featuring two water-cooled 18-core CPUs (36 cores total) and 256 GB of RAM. An earlier computer (a Dell T7500 with two 6-core CPUs and 96 GB of RAM) that has been used to execute many of the RF computations done to date in support of this program will also remain in service.

2. STATUS OF THE PLAN/SCHEDULE AND FUNDING

Figure 3 (next page) maps out the updated program plan, for quick reference. The reader may note, if comparing to our earlier reports, that there have been some adjustments. These stem variously from: our discovery and investigation of the (Bent) BAWSEA configuration; realization of the potential generalizability of *all* these antennas to the (Generalized) GAWSEA; and the challenges we have encountered and opportunities that have arisen along the way. At the time of this report, we are presently attempting to develop a more *practical* formalism/recipe to consistently yield *high-performance* RAWSEA designs.

The subject contract was awarded on 9/18/2013 and has an end date of 10/17/2016. The total contract value is $868,350, with current (per P00005 signed on 3/17/2015) allotted funding of $780,473. According to SARA’s accounting system, as of June 5, 2015, expenses and commitments (including fee) totaled $445,868, thus leaving $334,605 available, as of that date. If one simply compares the calendar and spending on this project, we have now consumed ~55% of the calendar and ~51% of the total contract value. We thank ONR for the continued support of this project.

There are no technical, schedule, or other funding-related program problems/concerns to report at this time.

[5] See, for example, http://www hamuniverse.com/feedlinelengths html

[6] This purchase is not a direct charge and so does not increase ONR’s costs or expenses under the subject program.

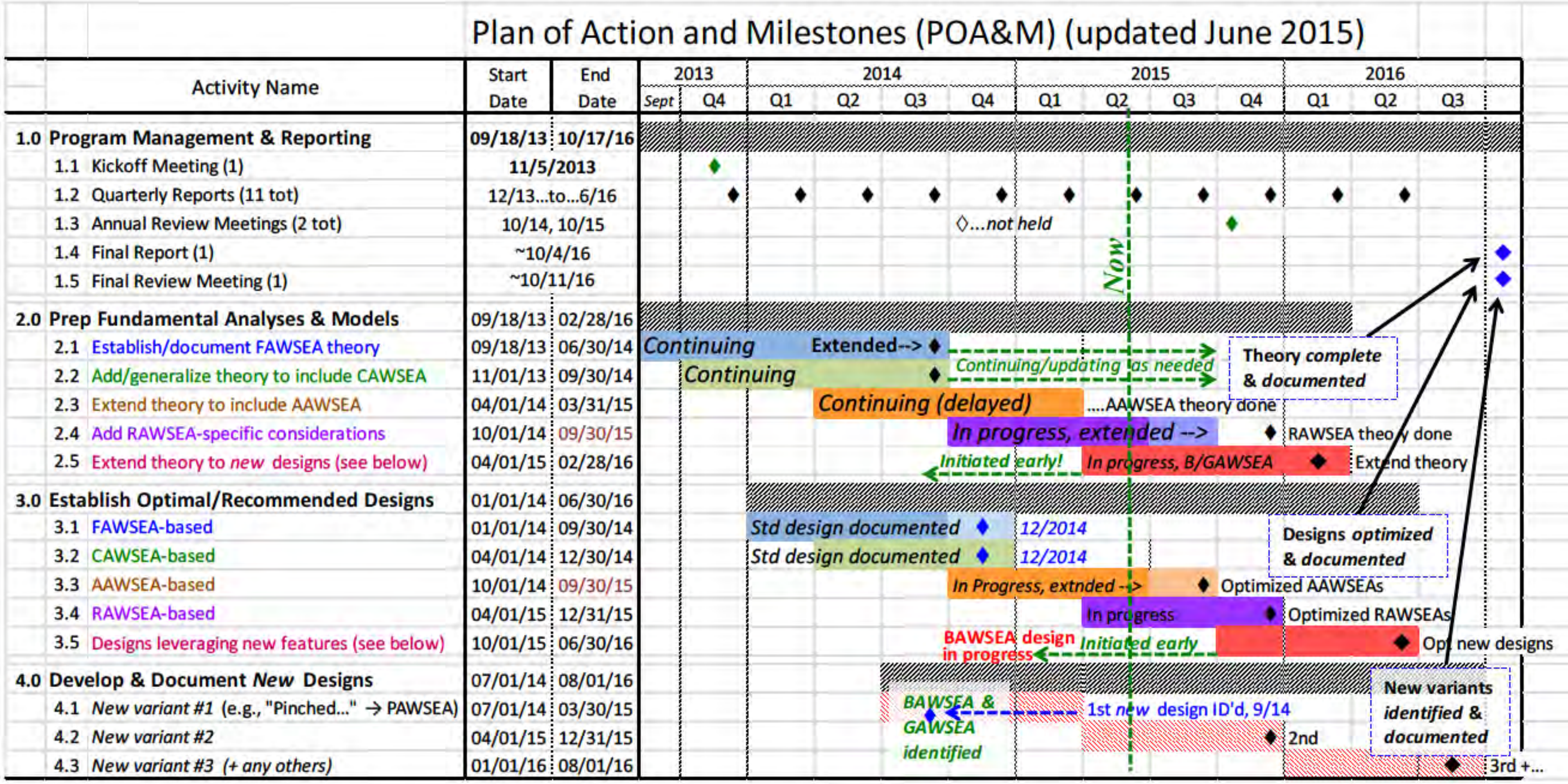

Figure 3. Updated Program Plan

3. RESEARCH AND ACTIVITIES PERFORMED THIS PERIOD

3.1. Continuing Research. RAWSEA Design and Optimization

As noted earlier, rotating the channels of a FAWSEA (to yield a RAWSEA), delivers the shallowest profiles among this family of shallow-depth antennas. A not-yet-optimized ("pre-standard") RAWSEA design based partly upon leveraging simplistic extensions of our FAWSEA design scripts, is shown via one of our numerical models in Figure 4. Some predictions and comparisons follow in Figure 5. This antenna has the *same* aperture area and aspect ratio as the "standard" high-performance FAWSEA documented previously. The waveguide channels are narrower (5.0 vs. 8.0 cm) and are rotated 70^{o}, to yield an overall antenna thickness ~70% of the aforementioned FAWSEA. Such an impressively low-profile could be highly-advantageous if seeking to integrate such an antenna into a very shallow package.

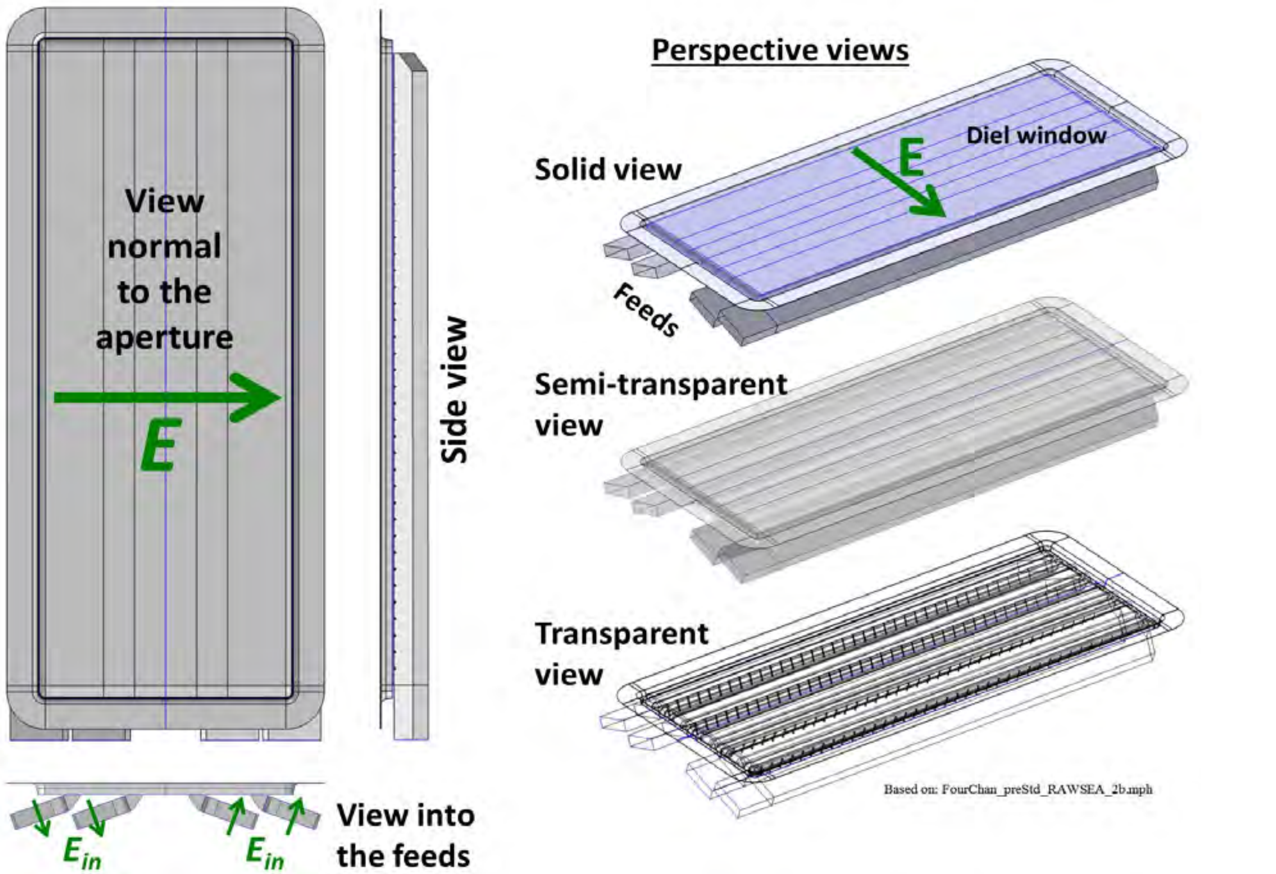

Figure 4. "Pre-standard" RAWSEA with 70^{o}-rotated channels. (Leaky-grill not fully-optimized.)

Only *half* of this antenna needs to be modeled computationally, since we can take advantage of geometric mirror symmetry. Alternative RAWSEAs with ~*translational* symmetry (e.g., Figure 2) are also possible, but are not truly left-right symmetric and thus require more computational resources to model properly. Regardless of whether the design symmetry is mirror-type, ~translational, or neither, the phases of the feeds should be chosen consistent with generating a unidirectional in-phase E *across* the aperture (not to be confused with *dependences* of those fields *along* the aperture, per the leaky forward-traveling wave). Performance differences between the above "pre-standard" RAWSEA embodiment and our "standard" FAWSEA include: (1) reduced gain, especially at the lower-frequency end of the range; and (2) failure of the beam *direction* to match the theory, pointing instead from ~2.0-3.5^{o} closer to the aperture normal.

The VSWR is also somewhat increased, but not dramatically. It should not be surprising that the microwave performance of this *naïvely-designed* RAWSEA is inferior to the FAWSEA on which it was based. And yet, the predicted performance is still quite respectable. (As another point of comparison, for all f > ~0.92 f_0, this antenna offers higher gain than our "standard" curvature-compensated CAWSEA.)

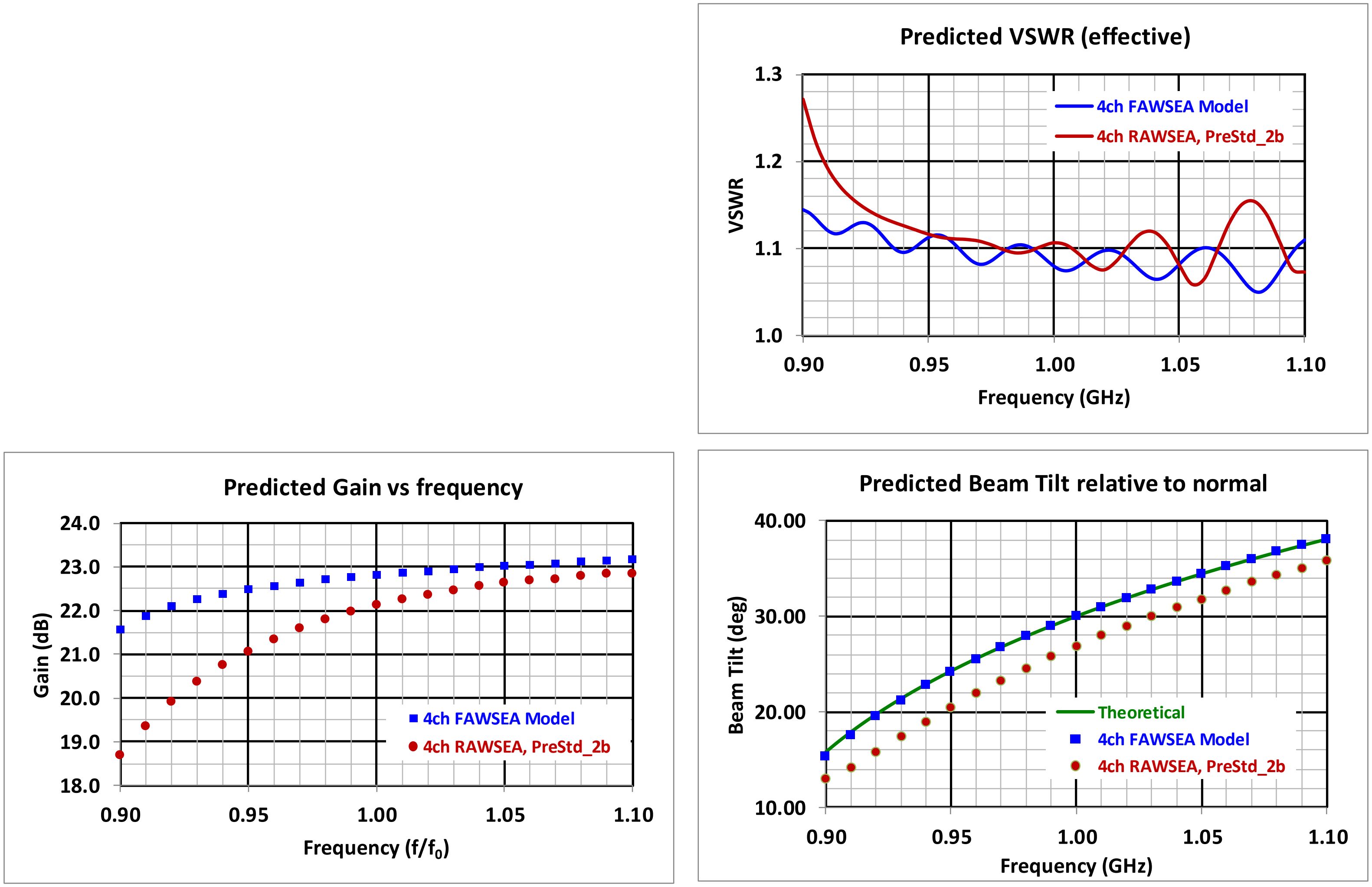

Figure 5. Comparing predicted performance of a "pre-standard" RAWSEA with a "standard" FAWSEA.

The result of an attempt at a "quick-fix" to the errant beam-direction is discussed next.

We can attempt a "quick-fix" to the beam tilt (see lower-right plot in Figure 5) to better match the theoretical curve at f_0 by adjusting the grill-wire plane, slightly increasing[7] the distance between it and the channel back-wall. The results are rather interesting. Predicted impacts upon the VSWR, gain, and beam direction, at 0.9, 0.95, 1.0, 1.05, and 1.1 f_0, appear in Table 1. The changes to the VSWR vary from helpful to negligible, while the disappointing gain at the lowest-end of the frequency range improved by more than 1.2 dB, and the beam direction now provides a ~good fit to the theory across the middle and upper-end of the frequency range. *However,* at the lowest-end of the range, the errant beam-direction is noticeably *over-corrected*. Even so, our "quick-fix" has nicely succeeded in delivering an across-the-range gain curve (and likewise, aperture efficiency) that for all points exceeds that of the "standard" compensated CAWSEA. Gain considered throughout the 0.9-1.1 f_0 range still lags the high-performing "standard" FAWSEA, so there remains opportunity for improvement.

Table 1. Performance Comparison: "Quick Fix"

Weaknesses in the Pre-Std RAWSEA are tagged in **red**.
Improvements due to the "quick-fix" are tagged in **blue.**

VSWR (effective) Comparison

Freq	Standard FAWSEA	Pre-Std RAWSEA_2b	After quick-fix shift of grill
0.9 f_0	1.145	**1.271**	**1.158**
0.95 f_0	1.113	1.116	1.072
1.0 f_0	1.080	1.107	1.064
1.05 f_0	1.082	1.081	1.048
1.1 f_0	1.110	1.073	1.078

Gain Comparison

Freq	Standard FAWSEA	Pre-Std RAWSEA_2b	After quick-fix shift of grill
0.9 f_0	21.573 dB	**18.694 dB**	**19.929 dB**
0.95 f_0	22.473 dB	**21.072 dB**	21.257 dB
1.0 f_0	22.813 dB	**22.120 dB**	22.053 dB
1.05 f_0	23.023 dB	**22.634 dB**	22.547 dB
1.1 f_0	23.174 dB	22.838 dB	22.845 dB

Beam Direction Comparison

Freq	Standard FAWSEA	Pre-Std RAWSEA_2b	After quick-fix shift of grill
0.9 f_0	15.3°	**13.0°**	**17.9°**
0.95 f_0	24.2°	**20.5°**	**24.7°**
1.0 f_0	30.0°	**26.9°**	**30.0°**
1.05 f_0	34.5°	**31.8°**	**34.2°**
1.1 f_0	38.1°	**35.8°**	**37.8°**

Perhaps the biggest disadvantage of such a "quick-fix" as applied above is its *ad hoc* nature. Simply stated, we need to better understand the RAWSEA. More light upon the path toward that understanding is provided by the investigation described below, which *supports* the view that the extra spacing (see Figure 2) in the curved section between the leaky-grill and the flared-aperture/window is (at least, very nearly) representable as an *equivalent* simple straight extension. For example, compare the plots for the single-channel models below (see Figure 6) that highlight the growth of undesirable standing waves in the leaky channel as we increase (without changing the wire-grill geometry) the *length* of an added straight extension (left column of the figure), or alternatively as we increase the *angle* of a curved extension (right column of the figure), recognizing that the latter is an essential feature of a RAWSEA.

Predicted H-plane beam directions and gains vs. RAWSEA channel rotation angle – and alternatively vs. a simple linear extension added between the leaky grill and aperture in a FAWSEA channel – are shown in Figure 7. Most tellingly, addition of the linear extension between the grill and aperture in a FAWSEA channel likewise causes *misdirection of the radiated beam*, *just as we saw with the RAWSEA* in Figure 5. These model-based analyses *confirm* that: (1) the curved intermediate transition sections unique to the RAWSEA geometry (e.g., see Figure 2) must (of course) not be ignored, and (2) the key to simplifying/ understanding these sub-sections is indeed to treat them as *equivalent* straight sections. We expect this approach to help us finally to include, and manage quantitatively, this essential piece of the theoretical puzzle as we continue to revise and improve our evolving set of design recipes.

[7] An increase of +3.4mm yielded the preferred beam direction (30.0°) for $f=f_0$, where f_0 =1.0 GHz.

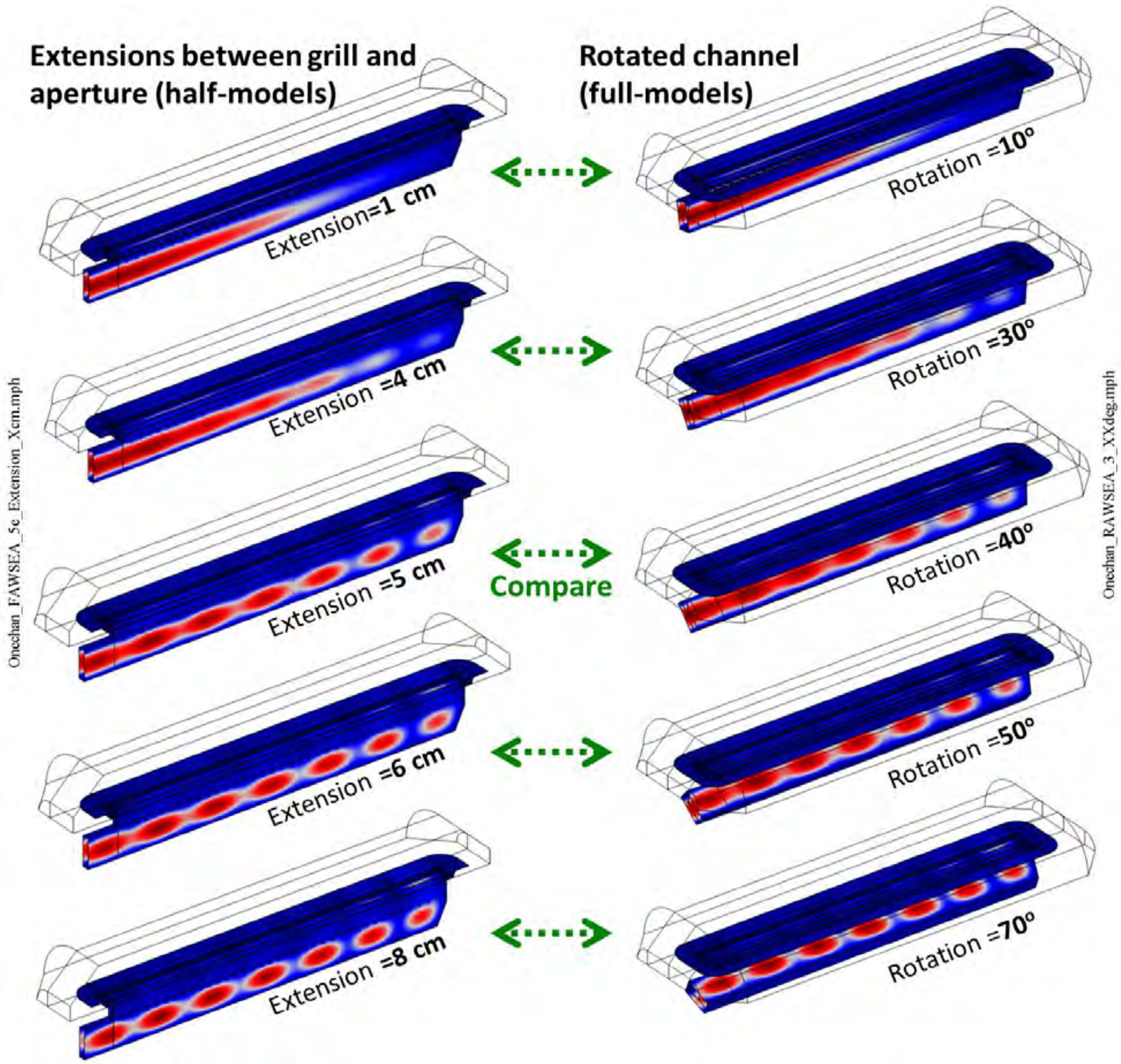

Figure 6. Note the strong similarities in the in-channel wave-reflection behavior, when comparing the impact of adding linear extensions (models in left column) between the leaky grill & aperture vs. the curved extensions (models in right column) that go along with rotating the channel. (All cases shown are for $f = f_0$.)

A partial/incomplete map of the aforementioned equivalence is provided by Figure 7. It is incomplete partly because it does not account for any frequency dependence. But we have the tools needed to flesh-out this mapping. That said, we caution the reader not to leap into assuming that the "effective length" is necessarily the product of a *fixed* effective-radius (e.g., the mean bend radius) and the channel rotation-angle angle $\Delta\theta$, ignoring frequency and local geometric details. For a highly-related/sobering discussion, consider the complexity of properly describing, with *theoretical rigor*, a simple E-plane waveguide bend[8].

[8] We refer here to the attempt by L. Lewin, "Theoretical analysis of the junction discontinuity between a straight and a curved section of rectangular waveguide," *Proc. IEE,* Vol. 124, pp. 511-516, 1977.

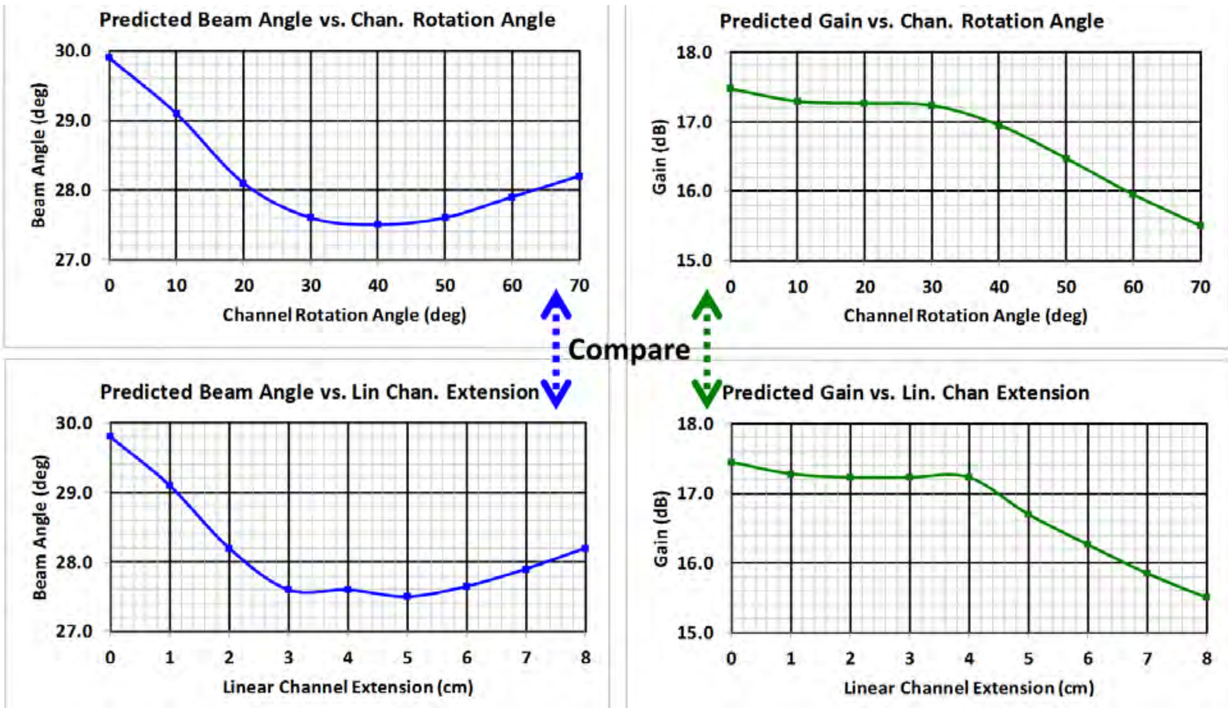

Figure 7. Further confirmation of ~equivalence of rotating the leaky channel vs. adding a linear extension. (All plots at $f=f_0$.) The models used here were also used to make Figure 6.

3.2. Pursuit of an Improved Circuit Model for a Flared (Curved-Edge) Aperture

Even for a single leaky-wave channel, the detailed behavior of the fields in the vicinity of an aperture which has been customized for HPM conditions is non-trivial. Recall that the *approximate* equivalent-circuit we developed previously[9] to model the transition of a finite-width channel to a half-space while featuring a *curved* (aka, flared) aperture was based on brute-force curve-fitting to results of numerous numerical models, spanning a limited parameter space. We have found that the result we obtained has proven less convenient to work with than we had hoped, in terms of serving as a general building block, so we are now seeking a *more formal* solution, more along the lines of those in the *Waveguide Handbook*. For reference, Figure 8 recaps the two different, but related, geometries being discussed.

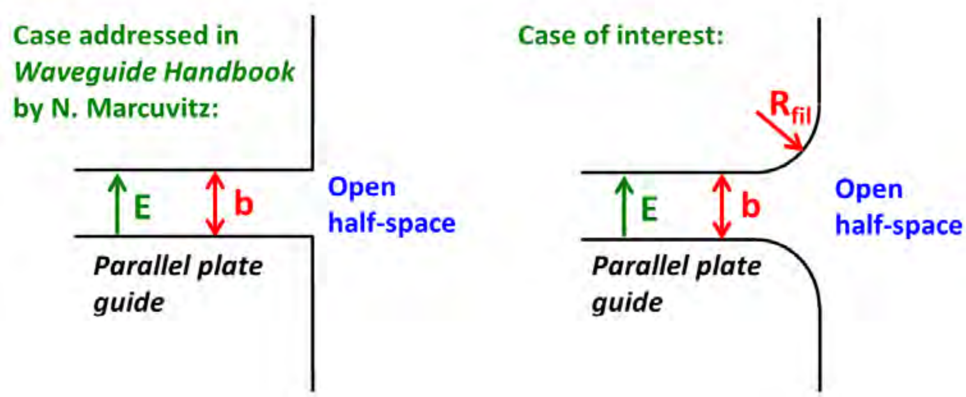

Figure 8. As noted previously[9], Marcuvitz provides an equivalent circuit for the configuration on the left, above. We have been employing an *approximate* circuit model (based on numerical models) for the case of more interest here (right, above).

[9] See our Second Quarterly Report for more information.

To this end, we are pleased to report that this problem in applied mathematics has been taken up as an informal research project *at no cost to ONR* led by the PI's wife, Prof. Deborah Koslover[10], an academic applied mathematician with some additional background in physics. In particular, Prof. Koslover is currently assessing the applicability to this problem (i.e. the right-side of Figure 8) of the mathematical methods[11] used successfully by Nathan Marcuvitz, Julian Schwinger[12], and others[13] to generate the circuit equivalents for the waveguide and transmission-line discontinuities and transitions documented in Marcuvitz's *Waveguide Handbook* and some other references. We will keep ONR apprised of her progress. If her investigation of this problem proves successful, the next stage will likely be to attempt to include the non-planer shape of the dielectric window. In that regard, we speculate that the work of Bodnar and Paris[14], who considered a dielectric-coated slot antenna via related formalisms, may be of some relevance here.

4. DISCUSSION, CONCLUSIONS, AND RECOMMENDATIONS

Research performed during this 7th quarter of the R&D program emphasized theoretical bases and engineering-recipe development (still in progress) of the RAWSEA antenna. A "pre-standard" RAWSEA design was prepared as an object of study during this process. It should be emphasized that in contrast to SARA's other RAWSEA designs prepared previously/prior to this ONR program, the aforementioned RAWSEA was *not* born solely via determined/iterative labor-intensive numerical modeling. Rather, this design was substantially guided by (1) the recipes/scripts developed under this program, and (2) our "standard" FAWSEA design. We are continuing to build up the theory, the design tools (recipes/scripts) and the library of "standard" models.

As always, we appreciate ONR's continuing support for this R&D.

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[10] http://www.uttyler.edu/math/faculty/dkoslover.php & https://www.uttyler.edu/math/curriculavitae/dkoslover.pdf

[11] These include Variational Methods, Integral Equation Method, Equivalent Static Method, Transform/Wiener-Hopf Method, etc.

[12] Schwinger, J., and D.S. Saxon, *Discontinuities In Waveguides - Notes on Lectures by Julian Schwinger*, Gordon and Breach Science Publishers, NY, 1968.

[13] For example, see Lewin, L., "The E-plane Taper Junction in Rectangular Waveguide," *IEEE Trans. Microwave Theory and Techniques*, vol. MTT-27, pp. 560-563, 1979.

[14] Bodnar, D.G. and D.T. Paris, "New Variational Principle in Electromagnetics," *IEEE Trans. Antennas & Propagat*, vol. AP-18, pp. 216-223, 1970.

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